ROTARY WING DECELERATOR USE ON TITAN

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ABSTRACT

Rotary wing decelerator (RWD) systems were compared against other methods of entry probe atmospheric deceleration and were determined to show significant potential for application to mission concepts requiring controlled descent, low-velocity landing, and atmospheric research capability on Titan. Design trade space evaluation and down-select results in a probe/lander with a deceleration system based on a single autorotating rotor utilizing cyclic pitch control.

First-order analytical models were developed for the conceptual design evaluation of an RWD descent system for use on Titan; this first-order analysis allowed the determination of the relationships between key design parameters and the overall time of descent of the entry probe. The possibility of extracting power from the entry probe rotor during descent was also investigated. Such a technique potentially could enable suites of high-power instruments during descent.

NOMENCLATURE

C_D	= drag coefficient
d	= rotor diameter
F_D	= drag force
F_G	= resultant force due to power extraction
F_W	= vehicle weight
g	= acceleration due to gravity
h	= descent altitude
m	= vehicle mass
P	= extracted power
$P_{windmill}$	= windmill-brake power
$t_{descent}$	= descent time
V	= descent velocity
η	= generator efficiency
ρ	= atmospheric density

1. INTRODUCTION

The ongoing Cassini mission to Saturn is considered one of the most successful international collaborations in the history of space exploration. The mission included the Huygens probe, which landed on the surface of Saturn's largest moon, Titan, in 2005, generating a large amount of scientific interest in further exploration of Titan. Huygens brought its power source with it in the form of batteries, which limited its operational lifetime to about six hours, nearly half of which was spent in atmospheric descent.

Titan's dense nitrogen atmosphere, methane hydrological cycle, and presence of water make it an especially interesting subject of study for atmospheric and planetary scientists. Huygens' success, combined with other recent findings, such as possible plate tectonics and cryovolcanism, provide justification for a return mission to study Titan's atmosphere and surface.

An entry probe and/or lander for such a return mission would greatly benefit from a descent system that can provide landing site selection, low-velocity touchdown, and power generation capabilities, while also providing a platform for atmospheric research. This paper provides a comparison of various atmospheric deceleration technologies for possible inclusion on a future mission to Titan based on their potential for providing heading control, a soft landing, and power generation during descent, and shows a rotary wing decelerator (RWD) system to be of significant merit. A conceptual design of such an RWD system is offered, as well as basic performance characteristics.

A rotary wing decelerator system uses rotating blades, like those on a helicopter, spinning in autorotation, to slow a descending vehicle down. The rotor is allowed to spin freely as the vehicle descends, which induces a large amount of drag. When the vehicle nears the surface/ground, the pitch of the blades (i.e. the rotor collective) can be increased in a stepwise fashion to harness the rotor angular momentum to increase as needed rotor lift for a low-velocity, or zero-velocity, touchdown – a.k.a. a "soft flare" – on a planetary surface. Autorotation and soft flare landings are designed into manned helicopters and are frequently practiced; such techniques are used for emergency landings in the event of engine failure.

2. ATMOSPHERIC DECELERATION METHOD SELECTION

The objective of this study is to consider the relative merits of rotary wing decelerators against other methods of atmospheric deceleration for Titan entry. Upon completing this initial assessment, the further goal of this study was to consider the viability of developing a low cost and weight rotary wing decelerator system that embodied controllable descent profile and landing site targeting, zero- or low-velocity touchdown, and, unique to this particular application, the potentiality of power generation capability for high-power scientific instruments during descent. Such an RWD system could enable improved atmospheric measurements during the descent phase of the mission, across all altitude ranges.

Five atmospheric descent/deceleration techniques were qualitatively assessed on their abilities to fulfill the requirements given above for a mission to Titan, relative to the capability provided by a parachute; refer to Table 1. These techniques were to use deployable surfaces to increase drag, a controllable parachute, retro thrusters, and an RWD system. The absence of a descent system was also included for purposes of comparison. A parachute was taken as the baseline deceleration system, as a parachute was successfully employed on the Huygens probe.

Table 1: Comparison of Descent Technologies

Concept	Parachute (Baseline)	None	Drag Surfaces	Controllable Parachute	Retro Thrusters	Rotary Wing Decelerator
Cost	0	+	+	–	–	–
Weight	0	+	+	–	–	–
Controllability	0	0	0	+	+	+
Landing Speed	0	–	–	0	+	+
Power Gen.	0	–	–	0	0	+
Atm. Research	0	–	–	0	0	+
Total	0	-1	-1	-1	0	+2

Qualitative metrics were assigned for each descent/deceleration system for cost, weight, controllability, landing speed, power generation capability, and suitability for atmospheric profile measurements. The Table 1 assessment clearly shows an RWD system to have significant potential merit over other deceleration systems. Later discussion in this paper will support the results of this initial assessment. But there is always a tradeoff. For example, the above comparison acknowledges that an increase in capability is most always associated with an increase in both cost and system weight.

The controllable parachute is shown to add very little capability for the increase in power and mass required by the associated navigation sensors and mechanical actuators. Augmenting a parachute with retro and directional thrusters, as are often used for Mars descent and landing, comes at a significant mass and cost penalty while serving only to reduce landing speed (while also disturbing the landing site). Huygens' final landing speed using only a parachute was about 5 m/s, so it is difficult to make case for retro thrusters solely on the grounds of increasing controllability or reducing landing speed.

Replacing the parachute with a rotor increases capability in all four areas. An RWD system provides the capability for a precise, zero-velocity landing. The system can generate power for its navigation sensors and atmospheric research during the descent by attaching a generator to the free-spinning rotor. An RWD system can additionally increase atmospheric research capability by varying its rate of descent, slowing down during traverse through key regions of the atmosphere, such as the tropopause, and increasing speed during areas of low interest to conserve power.

3. BASICS OF RWD SYSTEMS

There are many variations of RWD systems available, but all follow the same general sequence of events during descent. First, the vehicle enters the Titanian atmosphere and is slowed to approximately Mach 1.5, similar to Huygens' entry. At this point, the RWD system's protective cover is released, automatically deploying the rotors. As soon as they are deployed, the rotor (or rotors, if more than one are used) enter stall, behaving similarly to flat-plate drag surfaces. This slows the vehicle, and the rotors will soon de-stall and begin to rotate, gaining and storing momentum. Around this time, the vehicle slows further to about Mach 0.6 and the heat shield is released from the vehicle, allowing atmospheric data collection to begin.

The probe can now apply control actions to the spinning rotor system, inducing a forward glide through the atmosphere as it descends, allowing significant distance to be covered for aerial photography and atmospheric measurements. Because the rotor system is more efficient in forward flight, the horizontal glide phase increases the descent time, allowing additional time for data collection. As the probe nears the surface, the pitch of the blades is reversed, performing the soft flare maneuver, which lasts a total of about five to ten seconds. In this maneuver, the momentum stored in the blade is used to generate lift and enter a slow, tightly controlled descent, at the end of which the probe gently settles on the ground [1-2].

Rotary wing decelerators are not a new topic of study, and research into RWD application to planetary entry date back to the 1960s, when such systems were envisioned for ground-based recovery systems for Apollo. The most in-depth studies were carried out by the Kaman Aircraft Company, who demonstrated the feasibility of using a single-rotor RWD system, the "Rotochute," for atmospheric recovery systems. They found this system could be successfully deployed at velocities up to their testing limit of Mach 3 [1]. However, the availability and demonstrated reliability of parachutes slowed RWD development significantly.

Recently, RWDs have been reconsidered as a viable alternative to parachute-centric systems. In 2004, Young, et al, proposed an RWD system for atmospheric descent on Venus [3]. In 2005, Hagen proposed the use of an RWD system for NASA's Crew Exploration Vehicle [4]. Even more recently, in 2009, EADS Astrium developed an inflatable RWD system for Martian descent and landing as part of an ESA-funded study [2].

The dense atmosphere (greater than four times that of Earth), low gravity (nearly 1/8th that of Earth), and large atmospheric extent (over 160 km for deceleration and study) combine to make Titan even more ideal than Earth or Mars for the use of such a system. We build off these previous studies to present an RWD system for use on Titan.

4. RWD SYSTEM DRIVER ANALYSIS

Many variations of RWD systems are possible, providing a large design space. The general approach for picking a design was to determine the factors that drive the system and combine those factors into a few system architectures. These architectures were then compared on their relative merits, and the best option was selected as a baseline for preliminary and future analysis.

A list of system characteristics was created, shown in Table 2, each representing a choice between at least two options, which span the design space. From this list of properties, three were determined to be driving properties of the system, while the rest were characterized as "system details" and left for future study. Combinations of these driving properties result in vastly different RWD systems. Different combinations of the system details can then be applied to these systems to narrow in on a more specific design for a given application.

Table 2: System Characteristics

System Drivers	Options
Rotor Count	One, Two, Three, or Four
Blade Pitch Control	Cyclic Pitch Control, Collective Pitch Control
Heading Control	Pitch Control, Multiple Rotors, Variable CG
System Details	
Blade Count	One, Two, Three, or Four
Blade Size	Cyclic Pitch Control, Collective Pitch Control
Blade Position	Pitch Control, Multiple Rotors, Variable CG
Landing Style	Cyclic Flare, Powered, Vertical
Anti-Torque	Fins, Control Surfaces, Auxillary Rotor
Energy Storage	None, Battery, Capacitor, Flywheel

The three system drivers selected for comparison are the number of rotors, method of providing heading control, and the level of blade pitch control. The number of rotors is the most significant driving property, as varying the rotor count vastly affects the system. One rotor is the most common option in the literature [1-2,5], though systems with three or four rotors have been proposed [3]. Using two rotors complicates the design without providing any significant advantages, as such a system requires aerodynamic control surfaces that unnecessarily restrict the design and make landing more difficult.

The next system driver was heading control, which can be provided using a number of methods, but most notably by using pitch control, a variable center or gravity, multiple rotors, or control surfaces. Control surfaces were ruled out, as they will not be effective at the low velocities present during the landing phase of the mission. Varying the relative rotation rates of multiple rotors is the simplest option when multiple rotors are already present. The single rotor case can use either pitch control or vary its center of gravity (CG).

The last system driver was blade pitch control, as RWD systems can use cyclic pitch control, collective pitch control, or rigid blades. Rigid blades do not allow adequate descent rate control, especially during the landing phase, and thus cannot fulfill the system requirements. It only makes sense to use cyclic pitch control if pitch control is used for heading control; otherwise cyclic capability serves no purpose.

The resulting set of simplified RWD system drivers can be combined into only four architectures, as shown in Fig. 1.

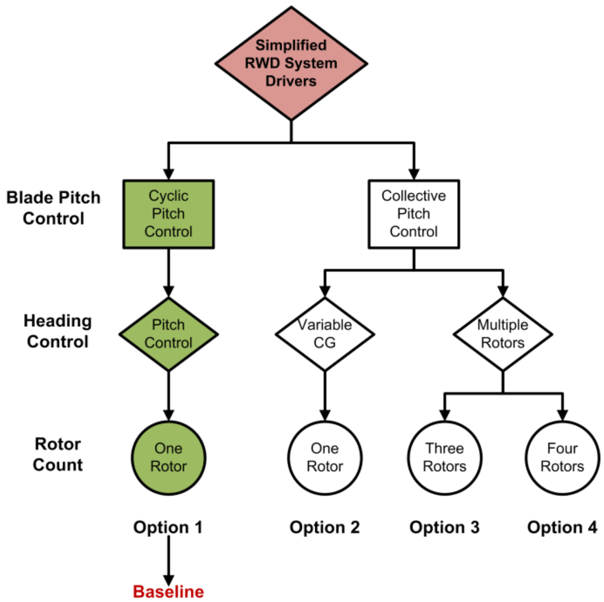

Fig. 1. Architecture Options

These resultant architecture options were compared based off their relative strengths in four areas: heading control, descent rate control, mechanical complexity, and power generation. Because the four options being compared are inherently different, a few assumptions had to be made. First, multiple rotors with collective pitch control were considered to be roughly equivalent in complexity to one rotor with cyclic pitch control. Second, it was assumed that a power system associated with a single large rotor would be more efficient than a power system associated with multiple small rotors. Third, it was assumed that it would be more difficult to control the heading of a three rotor system than a four rotor system.

Table 3: Comparison of RWD Architectures

Concept	Option 1 (Baseline)	Option 2	Option 3	Option 4
Heading Control	0	–	–	0
Descent Rate Control	0	0	0	0
Mech. Complexity	0	–	0	0
Power Generation	0	0	–	–
Total	0	-2	-2	-1

As shown in Table 2, Option 1 was taken as the baseline, as it was found to be the best fit for use on Titan. Advantages of this baseline system are numerous. First, because rotor area is related to diameter squared, one rotor is the most efficient from a mass standpoint. A quad-rotor system requires at least twice the total blade length to achieve equivalent performance. Second, having only one rotor simplifies vehicle design, rotor packing and deployment, and the power generation system. The variable CG control method offers less control capability at the cost of additional mechanical complexity.

5. VEHICLE DESCENT TIME

In order to show the capability of such a system and aid in preliminary mission concept evaluation, a first-order model was created to model probe descent time in Titan's troposphere as a function of vehicle mass and diameter. For the purposes of this preliminary design analysis, the system has been simplified to assume purely vertical motion, though autorotational systems are generally more efficient in forward flight. Additionally, the typical drag coefficient for a system in autorotation, C_D=1.23, was held constant throughout the analysis, though in practice it will vary based off other factors, such as blade rotation rate [6]. Atmospheric density was assumed constant throughout the troposphere; however, in reality the density decreases by almost 90% at the tropopause from its 5.75 kg/m3 surface value. Future updates to this model will include corrections for this behavior.

$$F_D = F_W + F_G \tag{1}$$

$$F_D = \frac{1}{8}\pi\rho d^2 C_D V^2 \tag{2a}$$

$$F_W = mg \tag{2b}$$

$$F_G = \frac{P_{windmill}}{V} \tag{2c}$$

The external forces on the vehicle during vertical descent are shown in Fig. 2 and Equations 1 and 2a-c. Drag force from the rotor acts to slow the vehicle. Using a generator to capture some of the energy of the rotor can be modeled as an additional force, acting to reduce drag and increase descent speed.

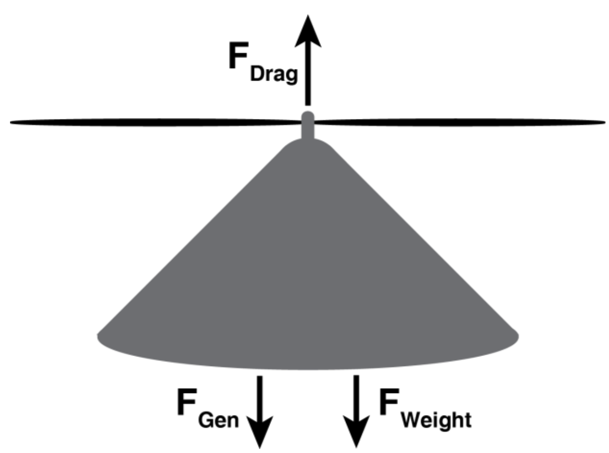

Fig. 2. Forces on RWD System During Descent

$$d = \frac{1}{V}\sqrt{\frac{8mg}{\pi\rho C_D}} \quad (3)$$

During standard descent, the probe will reach a steady state velocity when its drag force equals its weight [6]. From this, a relationship can be derived to determine the required rotor diameter for a given probe mass and desired descent velocity, presented in Eqn. 3. Fig. 3 shows the probe diameter necessary to achieve a desired descent rate on Titan for probe masses equal to or greater than that of Huygens (319 kg).

As Fig. 3 shows, low descent velocities require large rotor diameters. The simplest rotor is one in which no deployment or unfolding is necessary, however this limits the rotor diameter to fit within a rocket payload fairing, typically 5 m in diameter or less.

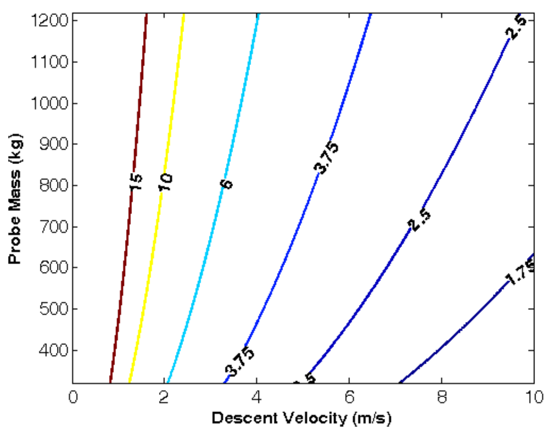

Fig. 3. Rotor diameter as a function of probe mass and desired descent velocity.

A simple deployment scheme is possible, as shown in Fig. 4, which deploys automatically upon release of the blades from the sides of the probe. If the main rotor shaft is lengthened, additional increases in rotor diameter are possible. Other strategies for increasing the rotor diameter include using an inflatable rotor [2] or telescoping blades [5], but these increase risk and complexity and are not required in Titan's dense atmosphere.

$$t_{descent} = \frac{hd}{\sqrt{\frac{8mg}{\pi\rho C_D}}} \quad (4)$$

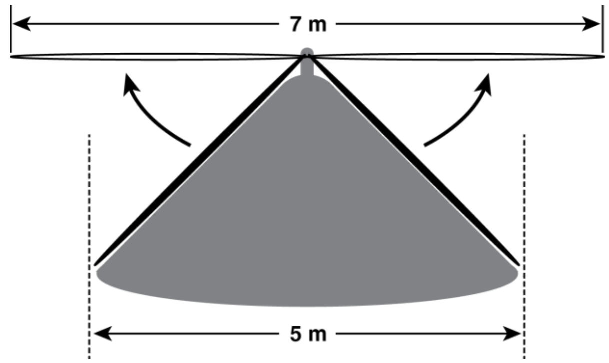

Fig. 4. Rotor deployment permits rigid rotor larger than probe body diameter.

A relationship was developed to predict total descent time of the probe from rotor diameter, as shown in Eqn. 4. For a constant mass, there is a linear relationship between rotor diameter and descent time, as shown in Fig. 5. Titan's tropospheric extent is 42 km (although the system would deploy at around 160 km in the much thinner upper atmosphere, similar to Huygens' parachute), so tropospheric descent times for a 500 kg probe can reach 6 hours with a 7-8 m rotor.

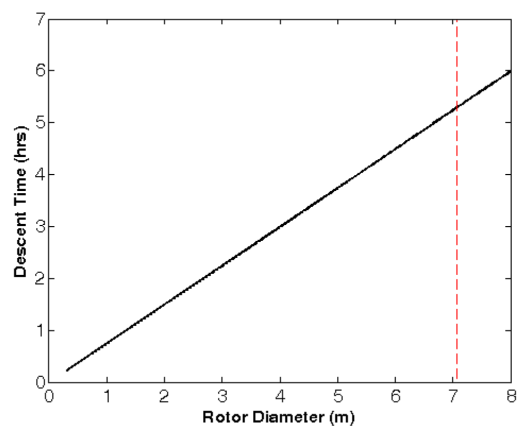

Fig. 5. Descent time as a function of rotor diameter. The dashed line represents the rotor from Fig. 4.

6. POWER GENERATION

It is possible that a portion of the energy of the descending vehicle could be used to power vehicle sensors, guidance systems, and research packages during descent. However, diverting some of the rotor's power with a generator will make the rotor less effective at slowing the vehicle, increasing descent velocity and reducing the total descent time. Eqn. 5 relates power output to descent velocity. This first-order model can be used for preliminary mission design purposes, and provides approximate results for small amounts of power extraction.

$$P = \eta V(\frac{1}{8}\pi\rho d^2 C_D V^2 + mg) \quad (5)$$

Fig. 6 shows the effect of power extraction on descent time for four vehicle configurations. Descent time is shown to be more sensitive to changes in probe diameter than to changes in mass. A heavy vehicle sheds more potential energy as it descends than a light vehicle, so although the heavy vehicle has a shorter descent time in ideal autorotation, its descent time is less sensitive to power extraction than the lighter vehicle.

7. EARTH, MARS, AND VENUS APPLICATIONS

This model is not unique to Titan, and descent times can also be calculated for other planets with atmospheres, including Earth, Mars, and Venus. Atmospheric densities, tropospheric altitudes, and gravitational constants for these three bodies can be found in Table 4.

Descent time as a function of rotor diameter is shown in Fig. 7. It is clear that both Titan and Venus have high potential for long-duration atmospheric descents using relatively small rotor sizes. For a 10 meter rotor, a tropospheric descent on Earth lasts only about half an hour, and only 15 minutes on Mars. This means RWDs are likely not the ideal platform for atmospheric research in these locations.

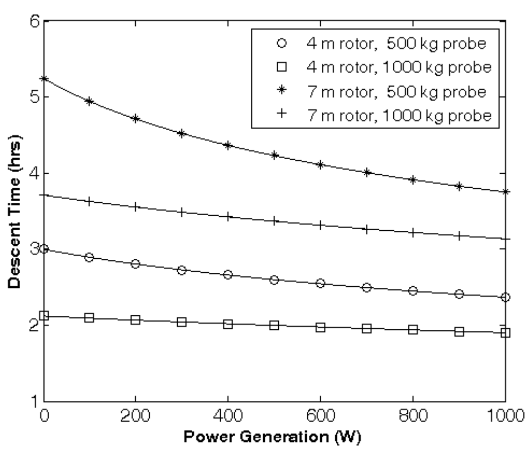

Fig. 6. Vehicle descent times in Titan's troposphere as a function of power extracted.

Table 4: Properties of Various Solar System Bodies

Planet	Atmospheric Density (kg/m^3)	Tropospheric Extent (km)	g (m/s^2)
Titan	5.75	42	1.345
Earth	1.20	17	9.80
Mars	0.02	40	3.71
Venus	65	65	8.87

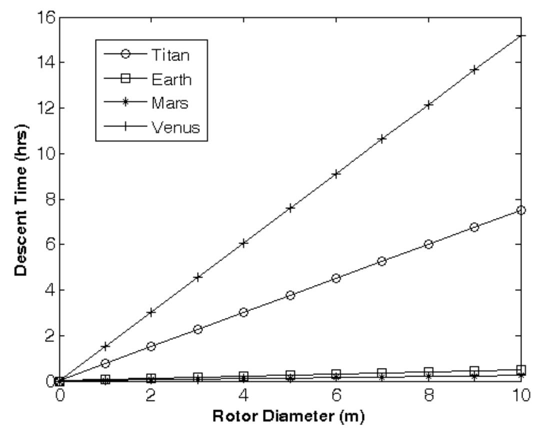

Fig. 7. Descent time as a function of rotor diameter for various solar system bodies.

8. CONCLUDING REMARKS

A rotary wing decelerator system shows great promise for atmospheric descent and landing on Titan, and would additionally serve well as a platform for atmospheric research. A single-rotor system using cyclic pitch control provides the ideal RWD system design for such an application, providing precision landing capability and the possibility of harnessing rotor energy for power generation.

Future work will focus on increasing model fidelity, working towards experimental verification of the system presented.

9. ACKNOWLEDGEMENTS

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